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RESEARCH MEMORANDUM

RECOVERY CORRECTIONS FOR BUTT-WELDED, STRAIGHT-WIRE THERMOCOUPLES IN HIGH-VELOCITY, HIGH-TEMPERATURE GAS STREAMS

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NATIONAL ADVISORY COMMITTEE
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SUMMARY

Recovery corrections were experimentally determined for several diameters of chromel-alumel and platinum 13 percent rhodium - platinum butt-welded thermocouples in a gas stream at temperatures from ambient to 2000° R and Mach numbers from 0.2 to 1.0. The recovery corrections at various temperatures and pressures are reasonably correlated with an empirical equation in which the correction is seen to be proportional to the fifth root of the pressure and inversely proportional to the fourth root of the temperature.

Probable errors in temperature measurement due to resultant uncertainties in the corrections are presented and discussed.

INTRODUCTION

It is a familiar fact that a body immersed in a gas may attain thermal equilibrium at a temperature other than that of the gas. For a gas at rest or moving at a low velocity, this temperature is the resultant of a balance of convective heat transfer between the body and the gas with the radiant and conductive heat transfer between the body and the external surroundings. For a gas moving at a high velocity, however, an additional factor becomes important: the aerodynamic heating effect, which is the result of friction and stagnation of the gas near the body.

For temperature measurements involving the immersion of instruments such as thermocouples in gas streams, corrections to the indicated temperatures are frequently necessary, and usually the errors in the measurements consist mainly of the uncertainty of the magnitudes of these corrections. A bibliography of the subject is given in reference 1.

For conditions of high temperatures and high velocities such as those encountered in jet-engine exhaust gases, the corrections for the heat-transfer effects and for the aerodynamic effects are of the same

order of magnitude. Methods for the calculation of the former are given in reference 2. The present work is concerned with the magnitudes and probable errors of the latter and is part of a program of high-temperature measurements being conducted at the NACA Lewis laboratory.

SYMBOLS

The following symbols are used in this report:

C_p	specific heat at constant pressure
D	diameter of wires
L	length of wires
M	Mach number
Pr	Prandtl number
p	static pressure
R	gas constant
Re	Reynolds number
r	recovery factor
T	total temperature
t	static temperature
t_{ad}	adiabatic temperature
v	velocity of gas
Δ	$\frac{T - t_{ad}}{T}$
γ	ratio of specific heats
ρ	density of gas
μ	viscosity of gas

ANALYSIS

The total temperature of a gas stream is defined by

$$T = t + \frac{V^2}{2C_p} \tag{1}$$

The relation between the total temperature and the temperature of a body immersed in the gas, for the case of zero heat transfer to external surroundings, is usually given in terms of a recovery factor r, which is defined by

$$r = \frac{t_{ad} - t}{T - t} \tag{2}$$

or

$$t_{ad} = t + r\,\frac{V^2}{2C_p}$$

where the adiabatic temperature t_{ad} is the temperature attained by the body in the absence of external heat transfer. The recovery factor is, in general, a function of the geometric configuration of the body and, in order of decreasing importance, of the Prandtl, Mach, and Reynolds numbers of the gas stream. A detailed discussion is given in reference 3.

For purposes of temperature measurement, it is more convenient to deal with a ratio Δ defined by

$$\Delta = \frac{T - t_{ad}}{T} \tag{3}$$

The relation of Δ and r is given by

$$\Delta = (1 - r)(1 - t/T) \tag{4}$$

Since the ratio t/T is primarily a function of the Mach number, Δ is a function of the Prandtl, Mach, and Reynolds numbers and of the geometry of the body.

Experience has shown that for the case of cylindrical wires in cross flow, the Mach number becomes an important parameter and the function may conveniently be assumed to have the form

$$\Delta = f_1(M,\ Pr)\times(Re)^n \tag{5}$$

Substitution in the Reynolds number of the relations (ref. 4)

$$\left.\begin{aligned} \rho &= p/RT \\ v &= M\sqrt{\gamma RT} \\ \mu &\propto T^{0.7} \end{aligned}\right\} \tag{6}$$

shows that

$$Re \propto \frac{MDp}{T^{1.2}} \tag{7}$$

and Δ may be written

$$\Delta = f_2(M, Pr)\, D^n \frac{p^n}{T^{1.2n}} \tag{8}$$

If the Prandtl number is independent of temperature and pressure, equation (8) may be written

$$\Delta = \Delta_0 \left(\frac{p}{p_0}\right)^n \left(\frac{T_0}{T}\right)^{1.2n} \left(\frac{D}{D_0}\right)^n$$

where

$$\Delta_0 = f_3(M)\, \frac{{D_0}^n\, {p_0}^n}{{T_0}^{1.2n}}$$

the subscript zero denoting reference conditions of pressure and temperature and a reference diameter. It may then be expected that for a given wire diameter

$$\Delta = \Delta_0 \left(\frac{p}{p_0}\right)^n \left(\frac{T_0}{T}\right)^{1.2n} \tag{9}$$

Similarly, at a given pressure and temperature the variation of Δ with diameter should be represented by

$$\Delta = \Delta_0 \left(\frac{D}{D_0}\right)^n \tag{10}$$

From the definition of Δ, the total temperature T is equal to the adiabatic temperature t_{ad} multiplied by a factor $1/(1 - \Delta)$. Since in practice Δ is much less than unity, this factor can also be expressed as $(1 + \Delta)$ so that Δ represents a fractional correction factor.

The present work was directed toward determination of whether formulas like equations (9) and (10) could adequately describe the dependence of Δ upon pressure, temperature, and diameter and, if so, toward evaluation of the exponent n. Considerable experimental data, accumulated over a period of years in the course of other research work, were analyzed for that purpose.

EXPERIMENTAL PROCEDURE

The recovery characteristics of thermocouples at elevated gas temperatures were obtained from tests made in the high-temperature tunnel described in reference 5 with a modified test section, shown schematically in figure 1. The modified test section consisted of three concentric Inconel cylinders 24 inches long, the outer one 6 inches in diameter, the inner one forming a nozzle approximately 2 inches in diameter. Gas flowed between the cylinders, and 12 thermocouples welded to the inner surface of the inner liner indicated that this surface was within a few degrees of the gas temperature under all conditions, thus establishing that net radiation between the test thermocouples and the surroundings was negligible. The gas temperature was measured with a 0.020-inch-diameter chromel-alumel thermocouple in the stagnation region. Preliminary tests showed this thermocouple to indicate the same as a high-recovery probe with a chromel-alumel thermocouple and as a platinum 13 percent rhodium - platinum thermocouple 0.020 inch in diameter placed nearby, to within wire calibration accuracies. The temperature was steady to within $\pm 5^{\circ}$ R, and no measurable gradients existed in the stagnation region or in the nozzle exit. The pressure ratio across the nozzle was measured with tubes in the stagnation region and in the plane of the nozzle exit as shown. The Mach number was calculated by using values for the specific heat ratio at the various temperatures obtained from reference 6. The test thermocouples were butt-welded and the junction reduced to wire diameter; they were installed with the wires extending across the jet as shown in figure 1. In all cases, a differential in temperature was measured between identical thermocouples in the stagnation region and nozzle exit with a sensitive recording potentiometer. The sizes of the wires tested were 0.032-inch- and 0.020-inch-diameter chromel-alumel and 0.020-inch- and 0.010-inch-diameter platinum 13 percent rhodium - platinum. In these tests the variation of the ratio Δ with Mach numbers from 0.2 to 1.0 was obtained at four approximate temperature levels: ambient, 1000°, 1500°, and 2000° R. In all tests for a given wire, the gas temperature was controlled to within $\pm 15^{\circ}$ R.

To determine the effect of pressure on recovery characteristics, chromel-alumel and platinum 13 percent rhodium - platinum thermocouples of various diameters were installed in a similar manner and tested at ambient temperature in a 3-inch air jet discharging into a receiver of controlled pressure. In these tests, the Mach number was varied from 0.2 to 1.0 at the approximate pressure levels of 15, 30, and 50 inches mercury absolute.

RESULTS AND CONCLUSIONS

Effect of Pressure and Temperature

The experimentally determined values of Δ at various temperatures are shown in figures 2 to 5 and at various pressures in figures 6 and 7; in each case, the values of Δ are plotted against the Mach number of the stream. Analysis of the data gives an average value of 0.2 for the exponent n in the expression obtained for Δ in the preceding section. Upon substitution of this value into equation (9), the equation becomes

$$\Delta = \Delta_0 (p/p_0)^{1/5} \, (T_0/T)^{1/4} \tag{11}$$

The degree of correlation may be seen in figures 2 to 7 where the data are presented as plots of Δ_0 against M, Δ_0 for this purpose being taken as

$$\left(\frac{p_0}{p}\right)^{1/5} \left(\frac{T}{T_0}\right)^{1/4} \times (\text{measured } \Delta)$$

The correlation appears sufficiently good to justify use of equation (11) for purposes of temperature measurements.

Effect of Wire Diameter

The diameter effect is noted in figures 8 and 9, where the results in tests on carefully welded and machined chromel-alumel and platinum 13 percent rhodium - platinum wires of various diameters at ambient pressure and temperature are presented. Analysis of the data similarly gives an average value of 0.2 for the exponent n in equation (10), which becomes

$$\Delta = \Delta_0 \, (D/D_0)^{1/5} \tag{12}$$

The correlation represented by equation (12) appears strictly applicable only at Mach numbers below 0.8. However, use of the equation at higher Mach numbers will not introduce errors greater than errors arising from other causes.

Effect of Fabrication Quality

Figure 10 shows the extent of variations of Δ with M from tests on several 0.040-inch and 0.020-inch chromel-alumel thermocouples which had not been precisely welded and had been hand-filed to approximate wire diameter. From these and similar tests it has been qualitatively observed that, in general, the poorer the construction of the junction, the lower the values of Δ throughout the range of Mach number; the variations, however, are quite unpredictable. This fact offers an explanation for the difference in the values of Δ against M at $T = 540^{\circ}$ R in the tests (figs. 2 to 5) performed in the high-temperature apparatus as compared with those (figs. 6 and 7) performed in the air jet. The former tests were performed at an earlier date when means were not available for accurate welding and machining of thermocouple wires; the latter tests were made when these means had become available but the high-temperature test facility no longer existed.

In the case of machined wires at ambient temperatures, there appears a pronounced maximum in the Δ against M curve at Mach numbers around 0.75. This effect presumably is the result of changes in the flow pattern around the wires and is related to similar effects observed in drag measurements on circular cylinders (ref. 7). The effect is noticeably reduced on the unmachined wires at low temperatures and appears to vanish at the higher temperatures. The reasons for this are not obvious.

Probable Value of Δ_0 and Its Probable Error

For the pressure range of 0.5 to 2 atmospheres, temperature range of 500° to 2000° R, and diameter range of 0.01 to 0.04 inch, the most probable value of Δ_0 and the probable error in this value are given in figure 11(a) for carefully machined wires and in figure 11(b) for all wires, regardless of character of fabrication.

If the value of Δ is experimentally determined for a particular thermocouple at room temperature and pressure, regardless of character of fabrication, the probable error to be expected when the wire is used at other temperatures and pressures and when correction equation (11) is applied is substantially the same as the probable error shown in figure 11(a). The probable errors shown in figures 11(a) and (b) represent probable errors on the order of 1/4 and 1/2 percent, respectively, in temperature measurements.

It should be pointed out that the results reported herein are strictly applicable only for butt-welded wires of great length compared with their diameters $(L/D > 50)$, perpendicular to the gas stream, and in a region free from interfering bodies. Should thermocouple wires be mounted in a holder of comparatively large diameter, large differences may be observed in the relation of Δ to M as a result of the interference effects; such a configuration would require calibration. The effect of the interference of the support is illustrated by the data published in reference 8 for a particular design of bare-wire type thermocouple probe. These data are also indicated in figure 11(a) for comparison with the data on very long isolated wires.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, July 23, 1954

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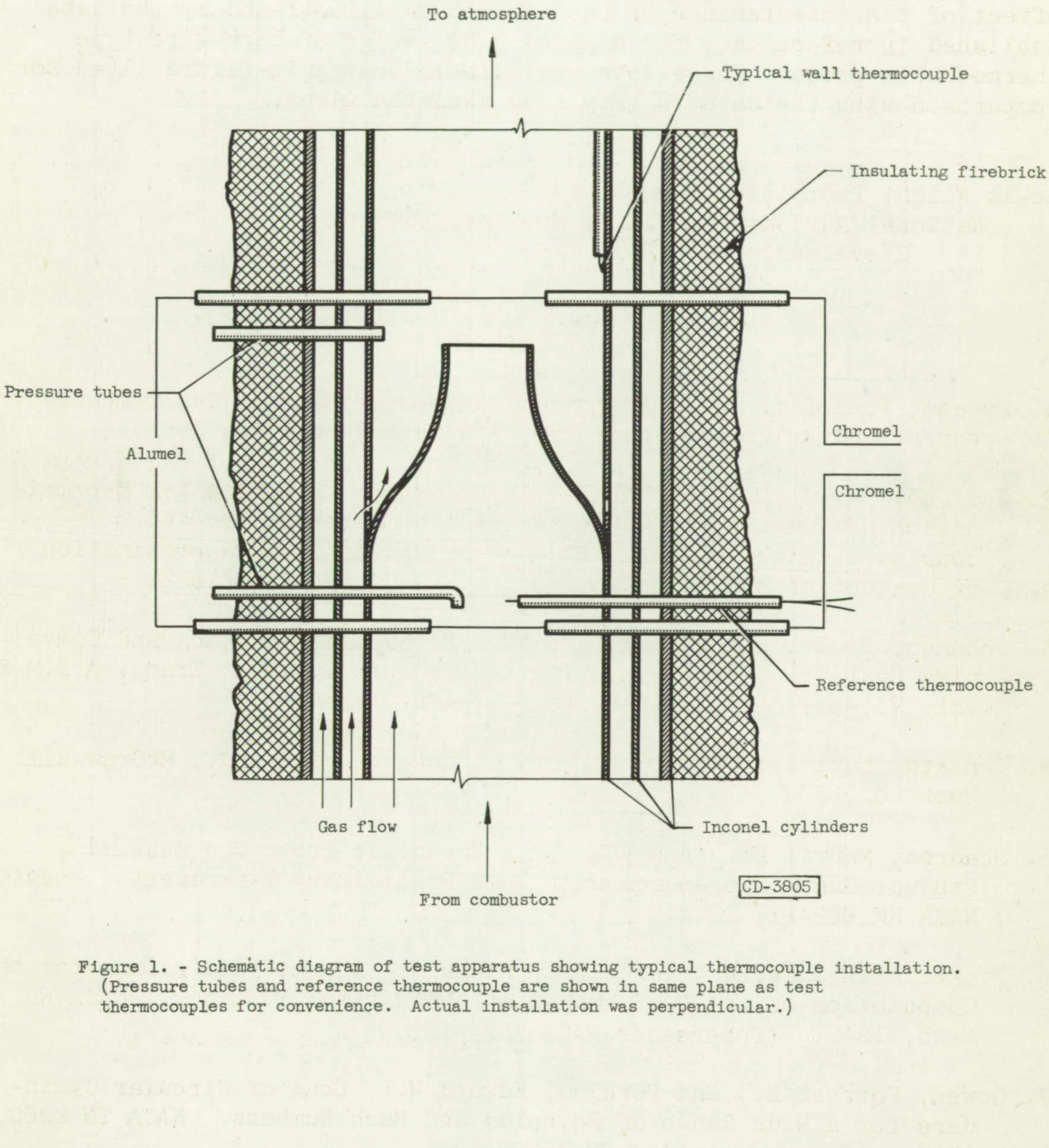


Figure 1. - Schematic diagram of test apparatus showing typical thermocouple installation. (Pressure tubes and reference thermocouple are shown in same plane as test thermocouples for convenience. Actual installation was perpendicular.)

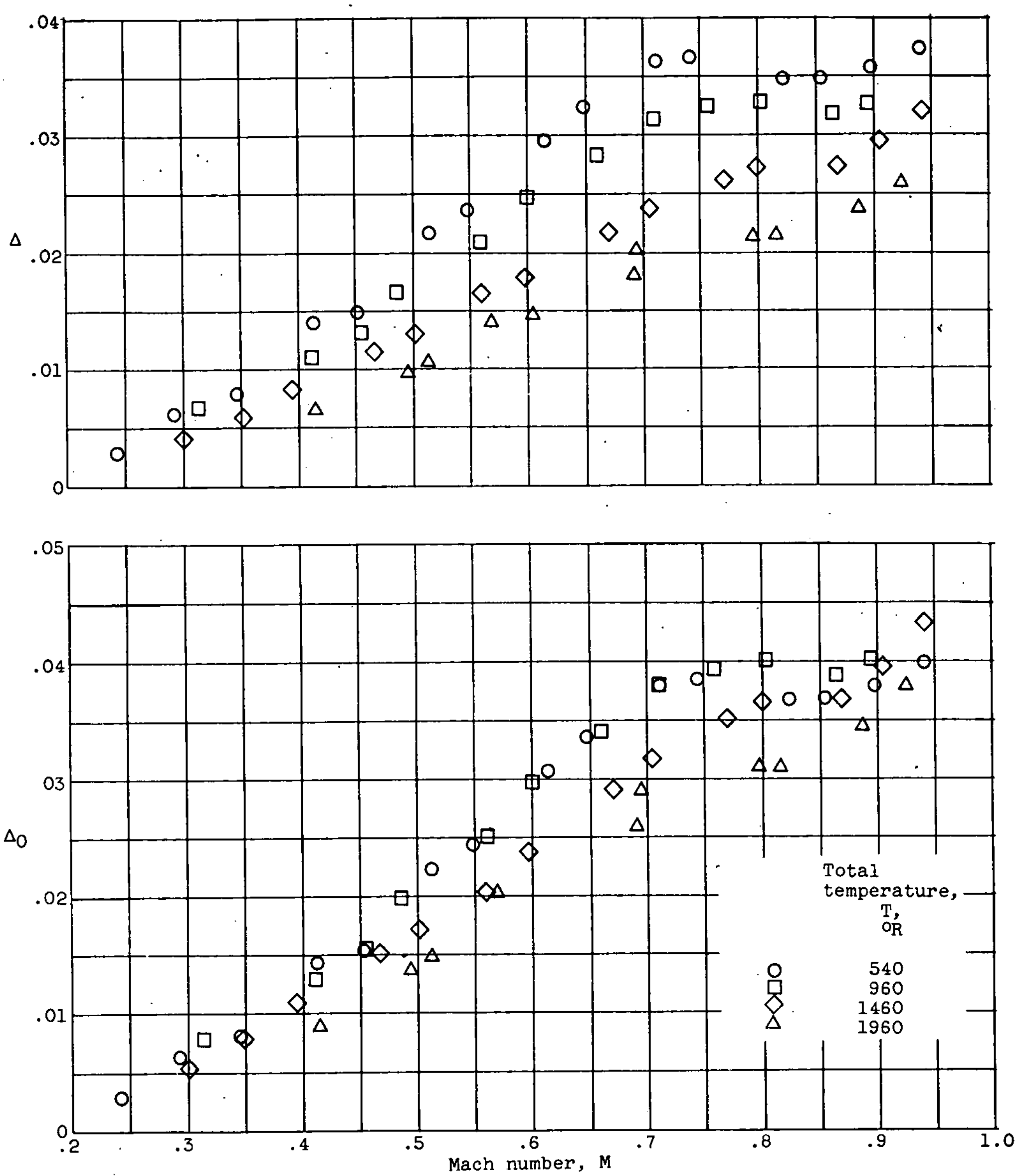


Figure 2. - Unmachined 0.040-inch chromel-alumel at various temperatures. Static pressure, 30 inches mercury absolute; reference total temperature, 540° R.

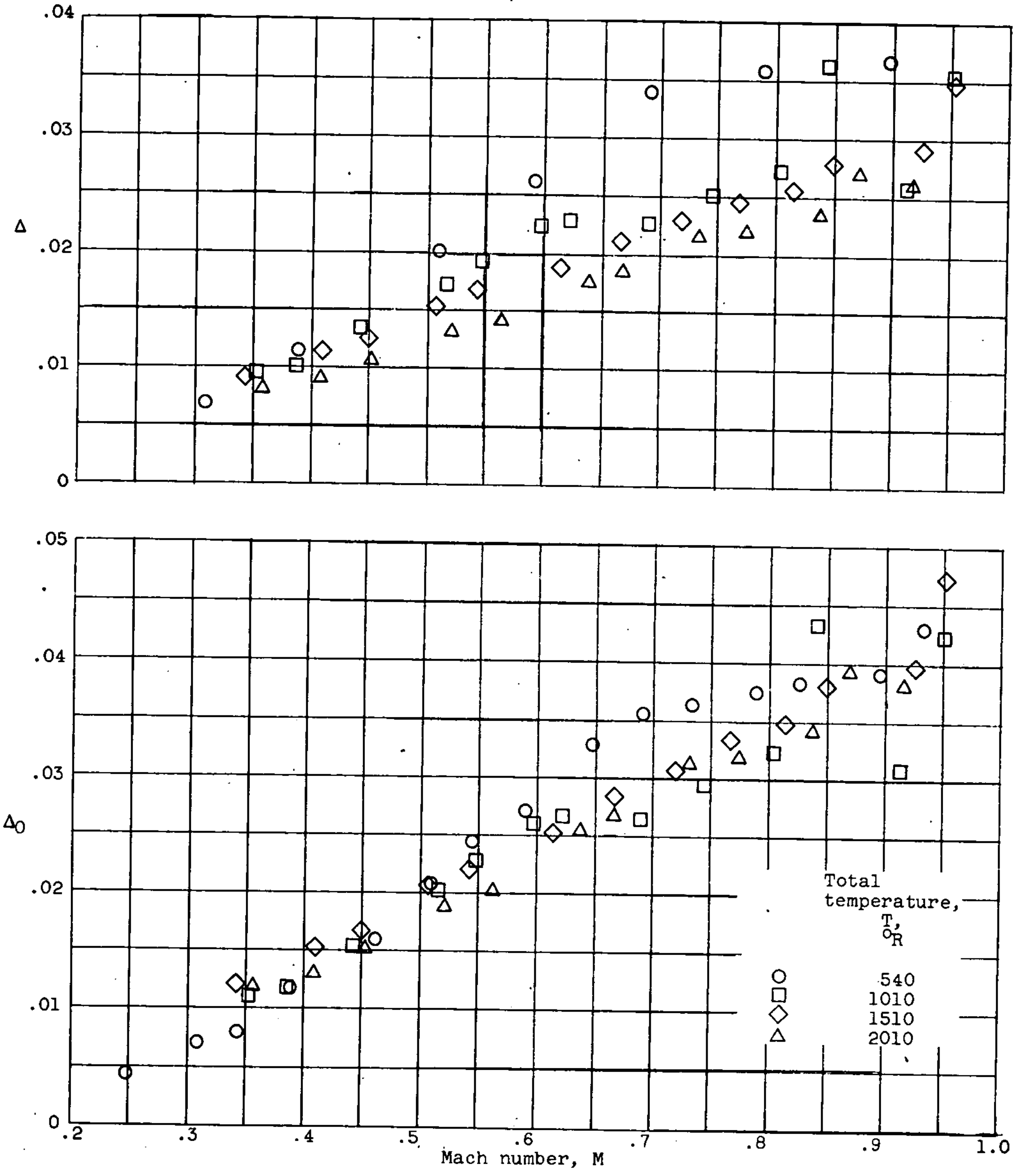


Figure 3. - Unmachined 0.020-inch chromel-alumel at various temperatures. Static pressure, 30 inches mercury absolute; reference total temperature, 540° R.

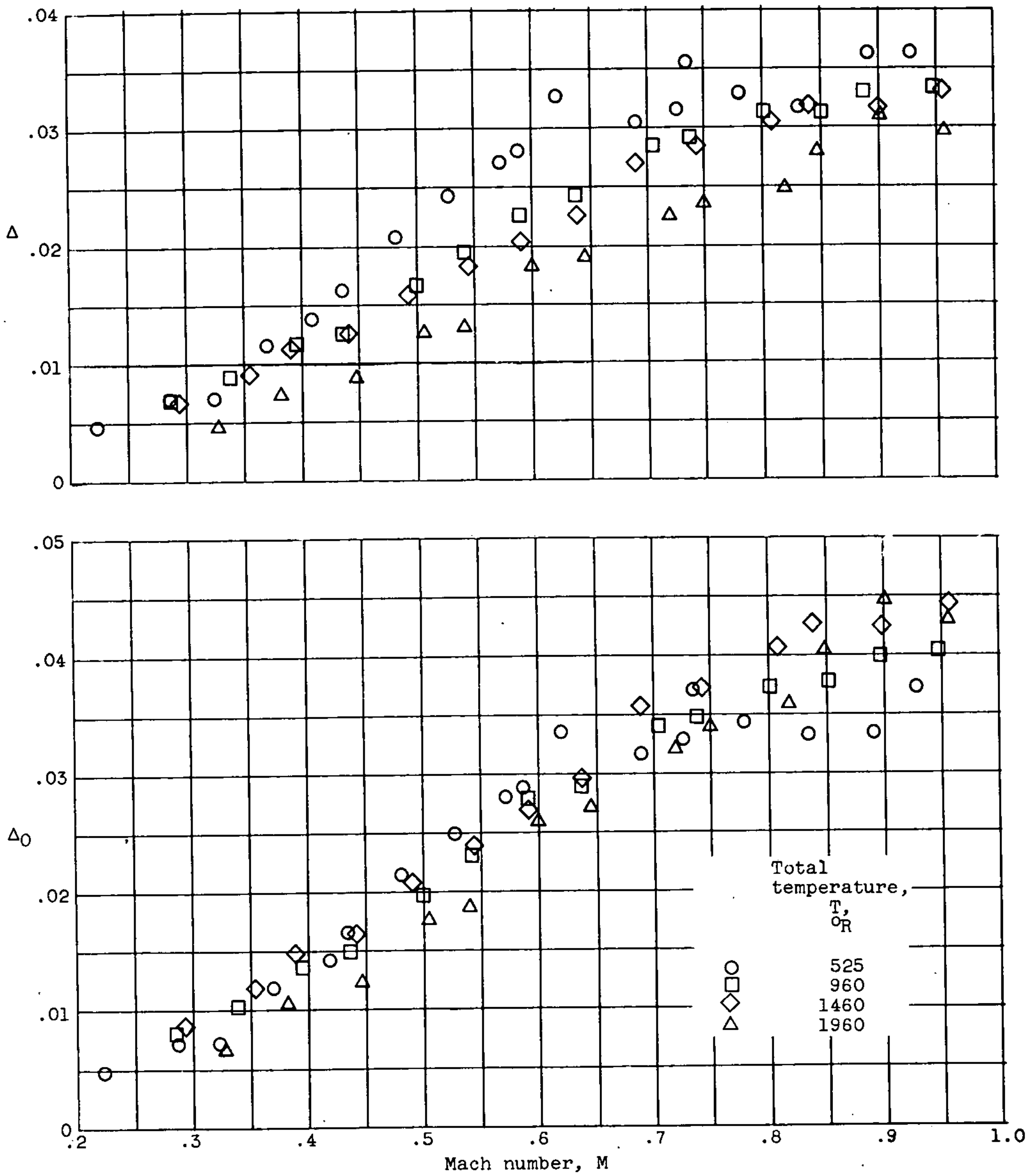


Figure 4. - Unmachined 0.020-inch platinum 13 percent rhodium - platinum at various temperatures. Static pressure, 30 inches mercury absolute; reference total temperature, 540° R.

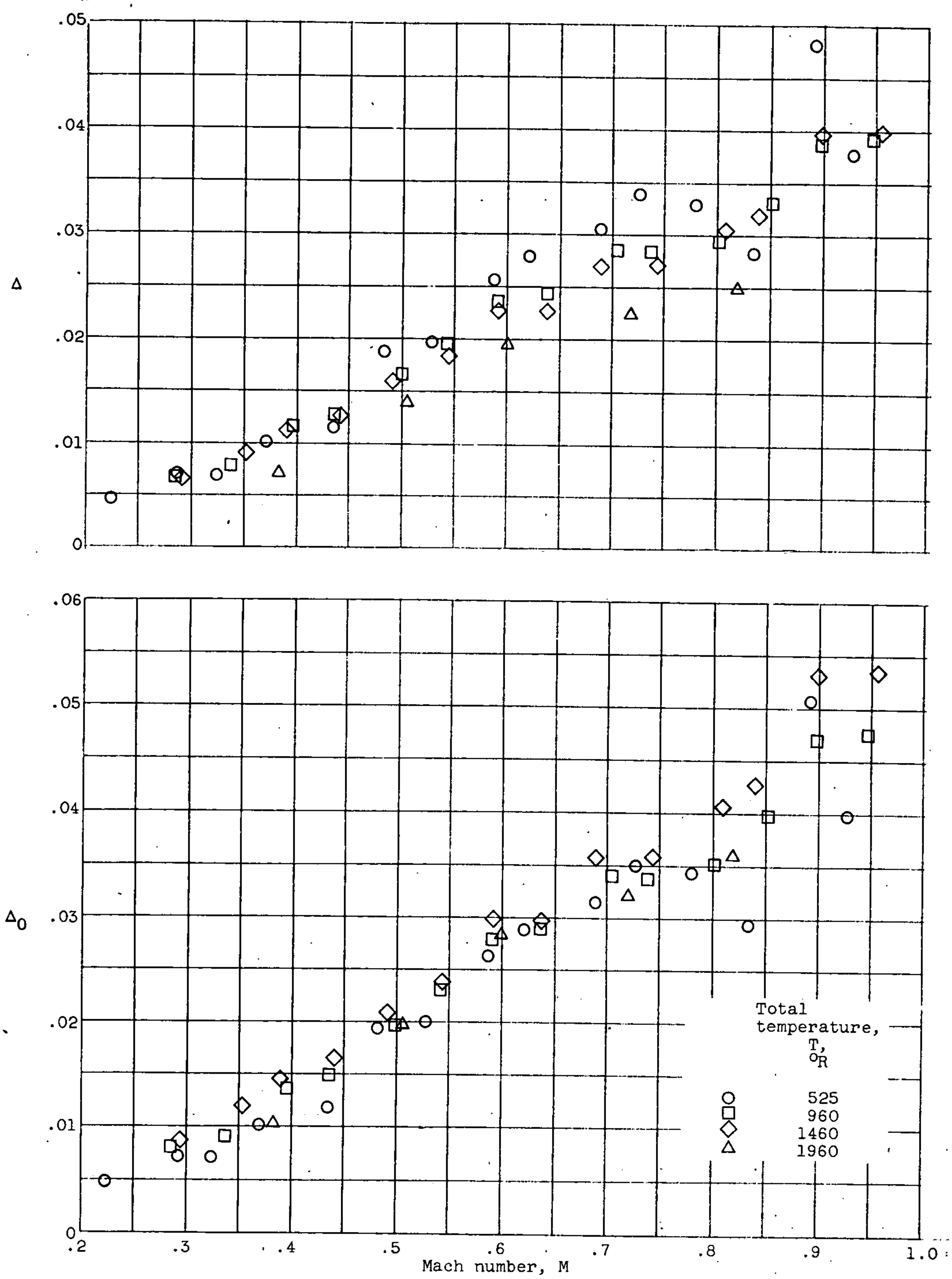


Figure 5. - Unmachined 0.010-inch platinum 13 percent rhodium - platinum at various temperatures. Static pressure, 30 inches mercury absolute; reference total temperature, 540° R.

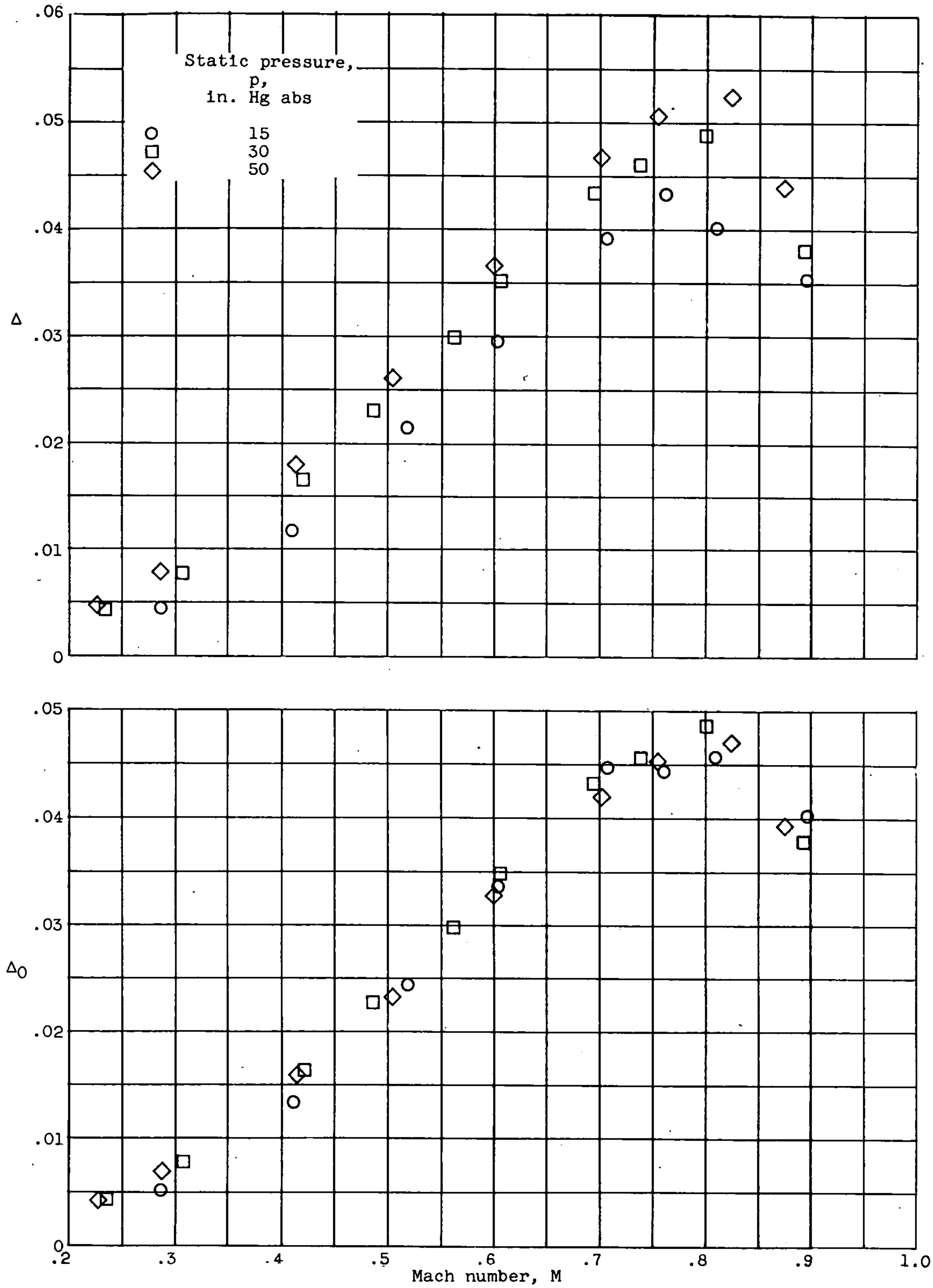


Figure 6. - Machined 0.025-inch chromel-alumel at various pressures. Total temperature, 540° R; reference static pressure, 30 inches mercury absolute.

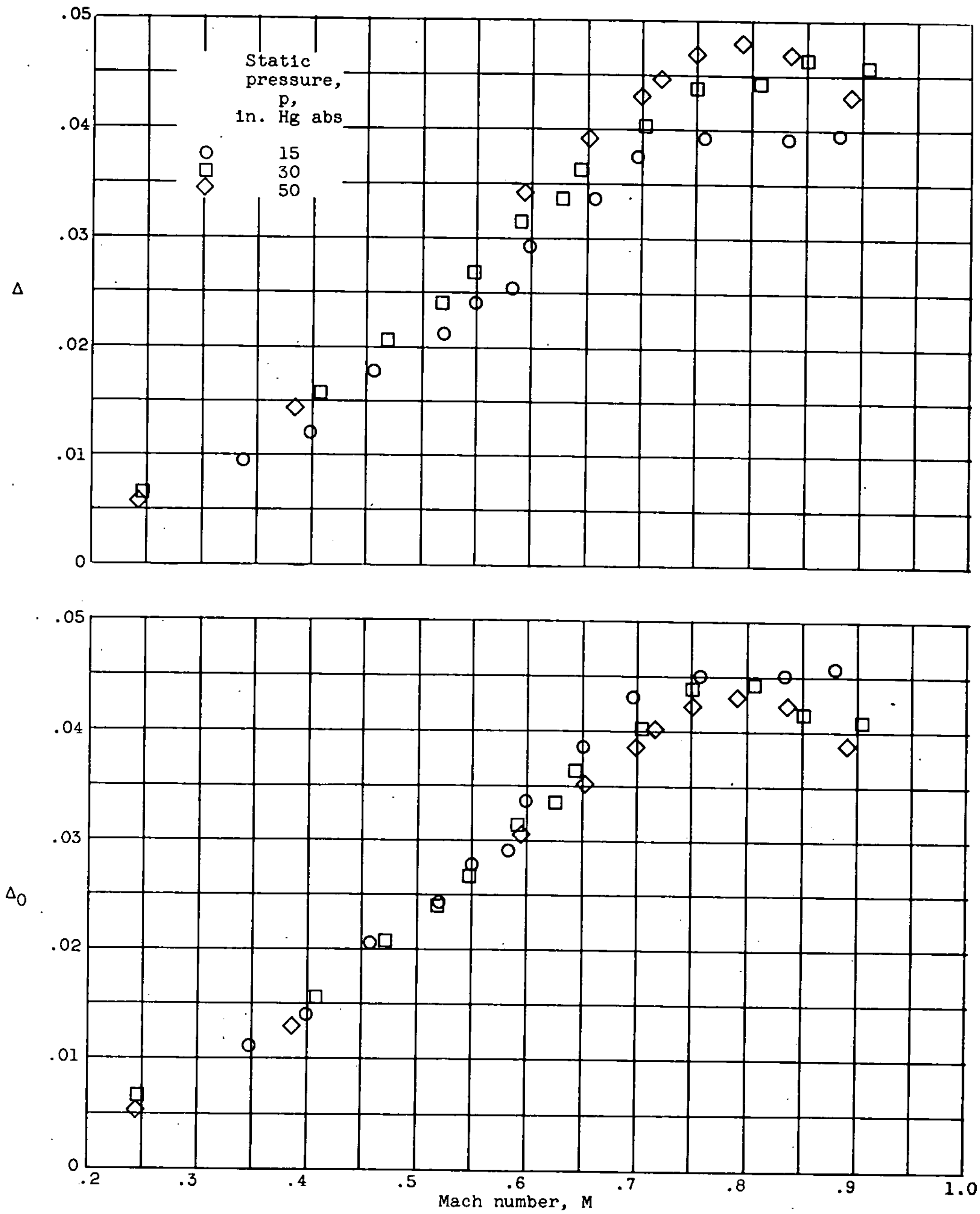


Figure 7. - Machined 0.019-inch platinum 13 percent rhodium - platinum at various pressures. Total temperature, 540° R; reference static pressure, 30 inches mercury absolute.

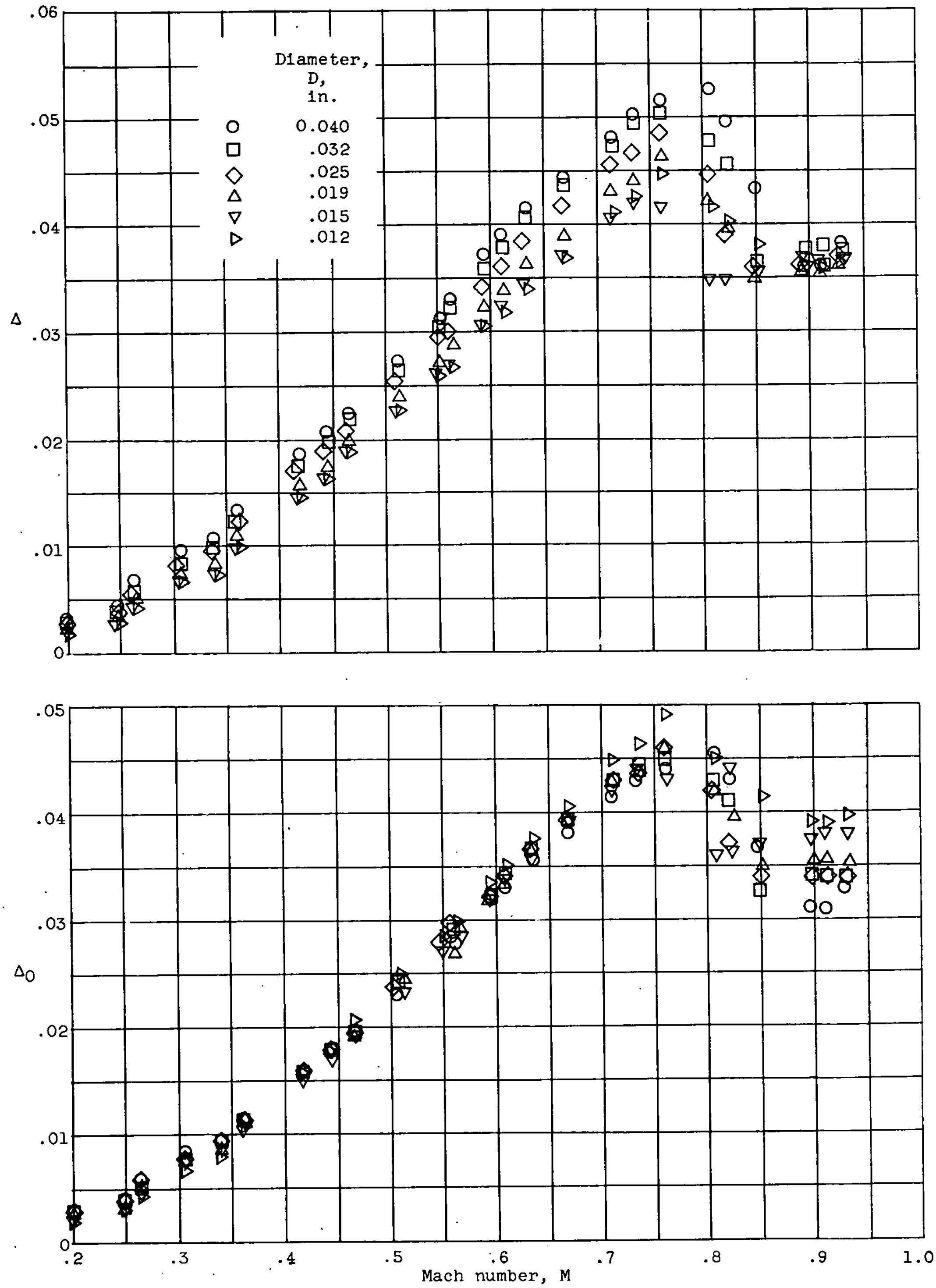


Figure 8. - Machined chromel-alumel of various diameters. Static pressure, 30 inches mercury absolute; total temperature, 540° R; reference diameter, 0.020 inch.

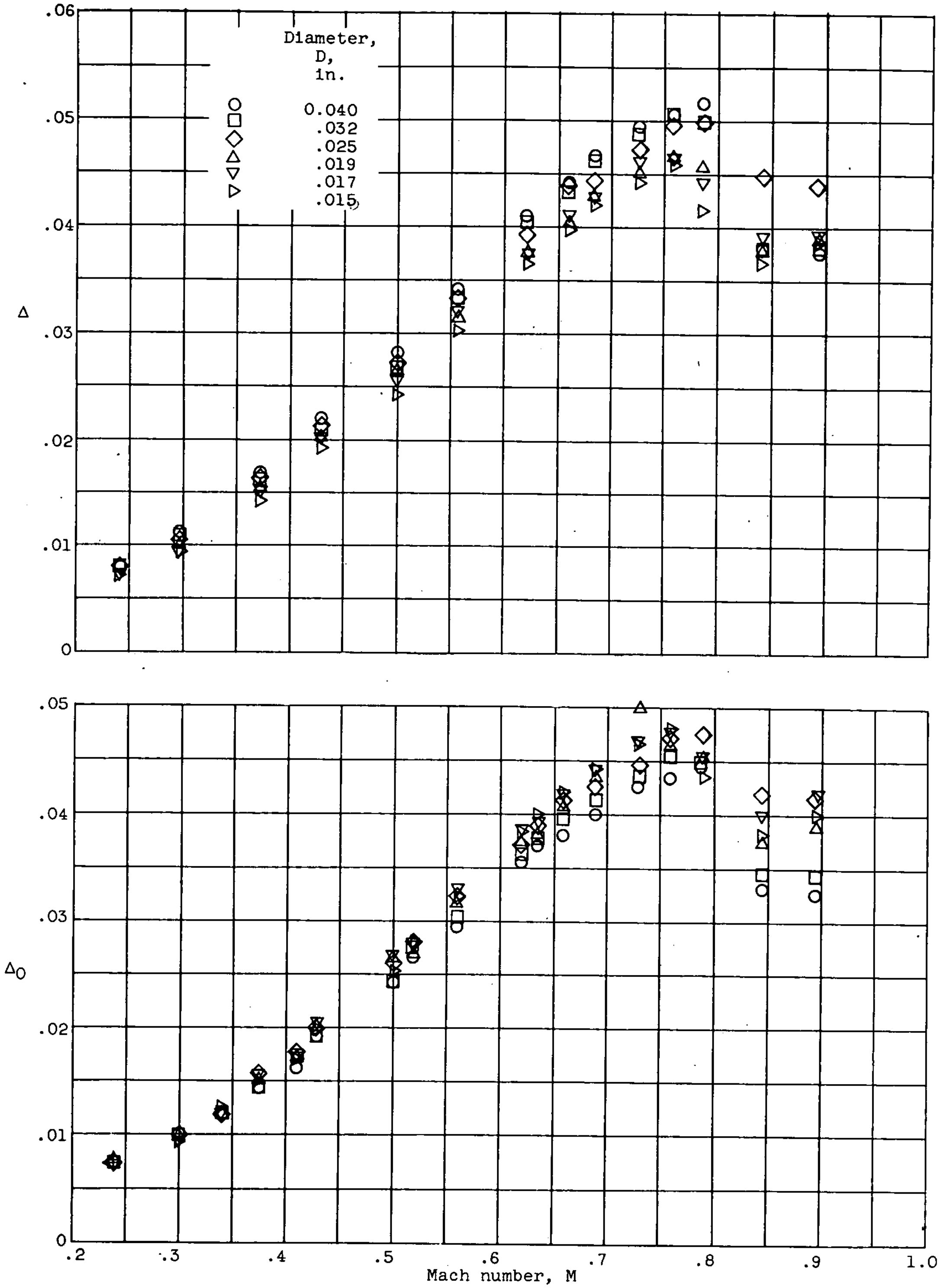


Figure 9. - Machined platinum 13 percent rhodium - platinum of various diameters. Static pressure, 30 inches mercury absolute; total temperature, 540° R; reference diameter, 0.020 inch.

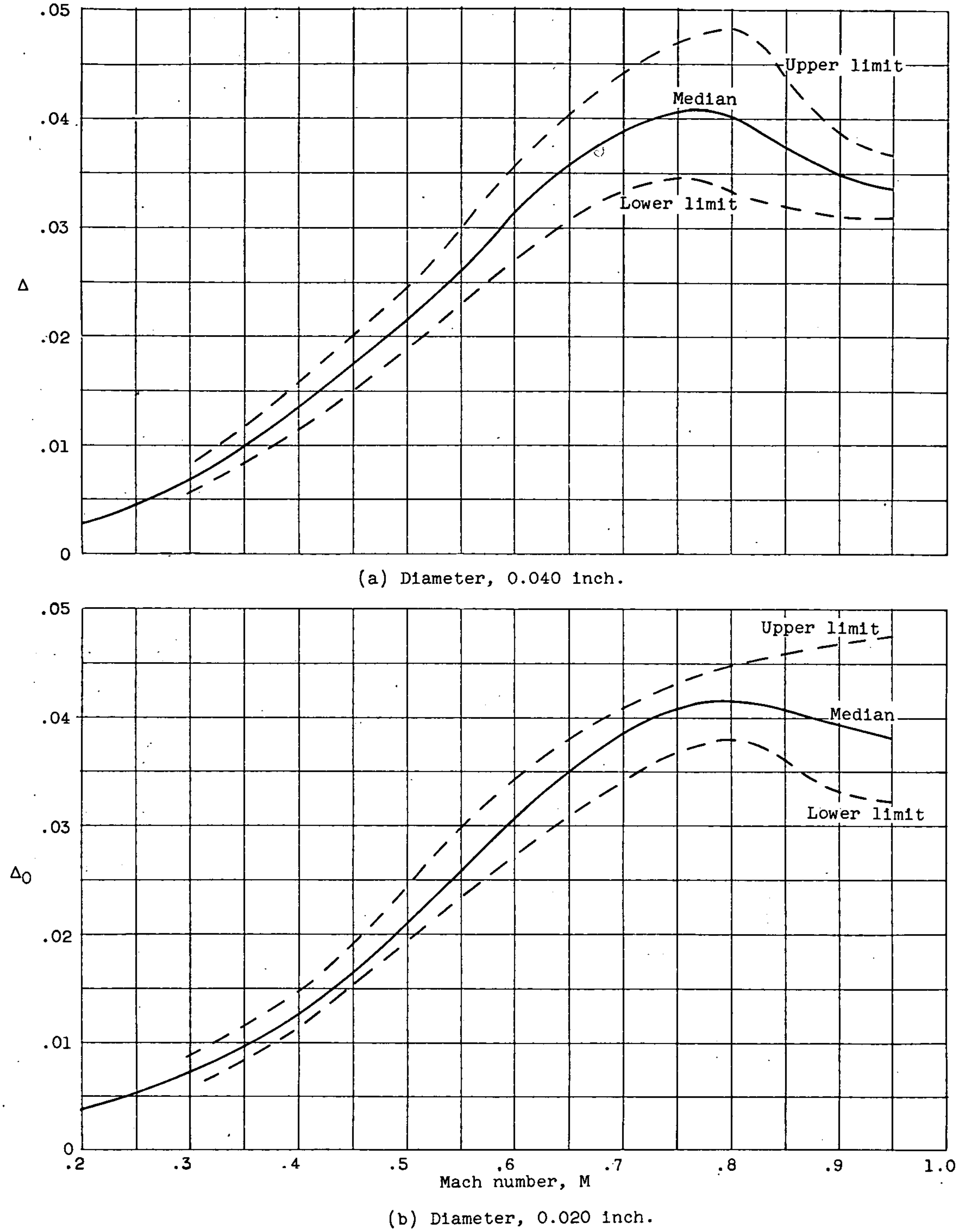
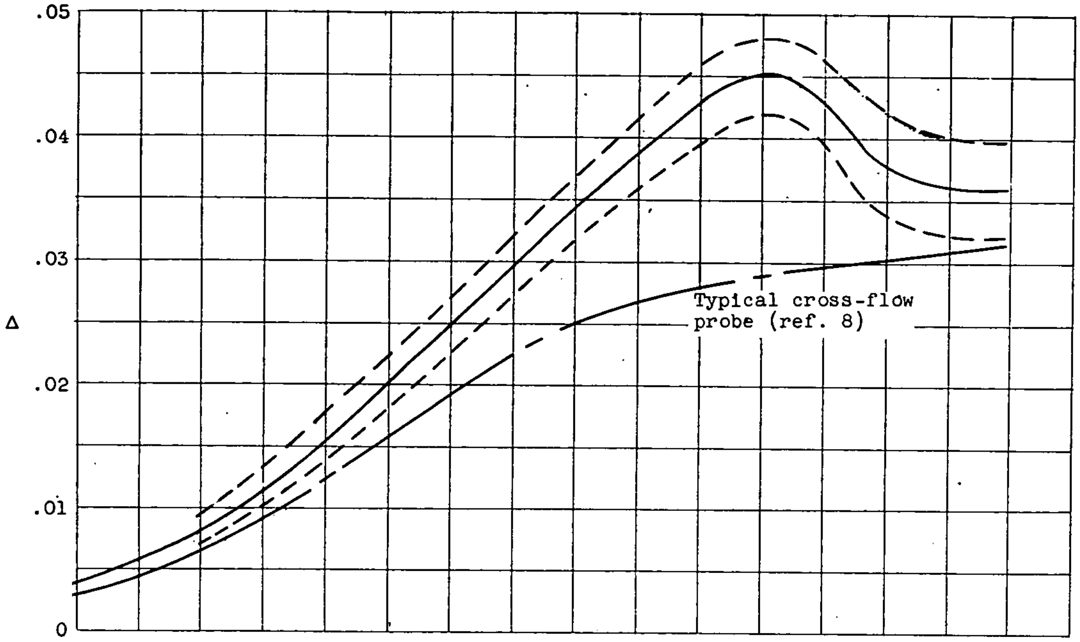
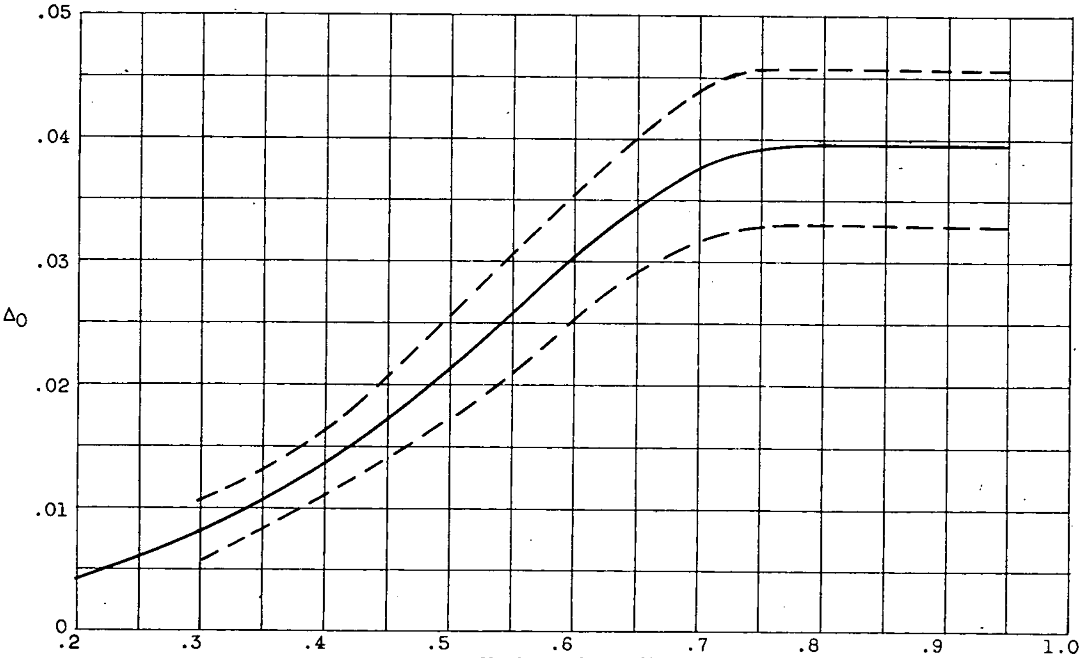


Figure 10. - Chromel-alumel wires of various character of fabrication. Static pressure, 30 inches mercury absolute; total temperature, 540° R.



(a) Machined wires.



(b) All wires regardless of character of fabrication.

Figure 11. - Mean curve and probable error at reference static pressure of 30 inches mercury absolute and reference total temperature of 540° R. Pressure range, 0.5 to 2 atmospheres; temperature range, 500° to 2000° R; diameter range, 0.01 to 0.04 inch; reference diameter, 0.020 inch.